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AD-A228 750

[illegible] to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, [illegible] the collection of information. Send comments regarding this burden estimate or any other aspect of this [illegible], to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson [illegible] of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

2. REPORT DATE	
3. REPORT TYPE AND DATES COVERED	FINAL 01 Jun 89 TO 28 Feb 90
4. TITLE AND SUBTITLE	SYMPOSIUM ON "THE ROLE OF LEDGERS IN PHASE TRANSFORMATIONS"
5. FUNDING NUMBERS	2306/A1
6. AUTHOR(S)	Professor Aaronson
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	Carnegie-Mellon University Metallurgical Eng & Matl Science Pittsburgh, PA 15213
8. PERFORMING ORGANIZATION REPORT NUMBER	AFOSR-TR- 90 1105
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	AFOSR/NE Bldg 410 Bolling AFB Washington DC 20332-6448 Dr. Alan H Rosenstein
10. SPONSORING/MONITORING AGENCY REPORT NUMBER	AFOSR-89-0334
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT	APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED
12b. DISTRIBUTION CODE	

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13. ABSTRACT (Maximum 200 words)

This is a final report on a symposium entitled "The Role of Ledges in Phase Transformations", sponsored by the Phase Transformations Committee of the ASM International-Material Science Division at the Fall, 1989 TMS-MSD Meeting in Indianapolis, IN. The oral presentation spanned six sessions of this seven (parallel) session Meeting. AFOSR provide travel support for four prominent overseas speakers, including Prof. J.H. van der Merwe (South Africa), Dr. R. C. Pond (University of Liverpool), Dr. M. Stobbs (Univ. of Cambridge) and R. R. Bonnet (Grenoble). Smaller support sums, also for overseas participants, were received from JOEL and from ALCOA Technical Center. These contributions were vital to the success of the symposium, since it was necessary to draw upon a wide range of international talent in order to develop the program properly. Collection and review of paper for publication is now nearly completed; publication within one, or at the most two issues of Metallurgical Transactions A is planned in the near future. A copy of the program is attached to this report.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED

Final Technical Report

from

Department of Metallurgical Engineering
and Materials Science
Carnegie Mellon University

to

Air Force Office of Scientific Research
Electronic and Solid State Sciences
Bolling Air Force Base
Washington, DC 20332

on

Symposium on the Role of Ledges in Phase Transformations

by

H. I. Aaronson, Principal Investigator

September 17, 1990

Final Technical Report on a Symposium concerning "The Role of Ledges in Phase Transformations"

This is a final report on a symposium entitled "The Role of Ledges in Phase Transformations", sponsored by the Phase Transformations Committee of the ASM International-Materials Science Division at the Fall, 1989 TMS-MSD Meeting in Indianapolis, In. The oral presentations spanned six sessions of this seven (parallel) session Meeting. AFOSR provided travel support for four prominent overseas speakers, including Prof. J. H. van der Merwe (South Africa), Dr. R. C. Pond (University of Liverpool), Dr. M. Stobbs (Univ. of Cambridge) and Dr. R. Bonnet (Grenoble). Smaller support sums, also for overseas participants, were received from JEOL and from ALCOA Technical Center. These contributions were vital to the success of the symposium, since it was necessary to draw upon a wide range of international talent in order to develop the program properly. Collection and review of papers for publication is now nearly completed; publication within one, or at the most two issues of Metallurgical Transactions A is planned in the near future. A copy of the program is attached to this report.

Research workers in many countries and in many different research areas have gradually come to realize that ledges play a central role in the growth of crystals from the vapor, liquid and solid phases. However, the structure of ledges is not easy to study experimentally or to analyze theoretically. Similarly, the kinetics of ledgewise growth pose substantial problems to the experimentalist intent on their measurement and to the theoretician attempting to account for these data mathematically. Both experimental and theoretical studies during the three major types of phase transformation enumerated have tended to develop more or less independently of each other. The organizers of this symposium, Professors J. M. Howe and H. I. Aaronson, Department of Metallurgical Engineering and Materials Science, Carnegie Mellon University, sought to bring together major representatives from all three research areas to describe their progress, conclusions and concerns in the hope that achievements in one area would help workers in the other two. How well this symposium has succeeded in its objectives will take some years to determine through evidence gathered from referencing patterns in the literature. However, as indicated in this report a number of major issues in this field of research were prominently highlighted during the symposium. It is hoped that the resulting focussing of attention will accelerate progress in elucidating the role of ledges in all three types of transformation through which crystalline product phases are produced.

After an introductory overview by H. I. Aaronson, the next three speakers discussed the observation of ledges with TEM and the following speaker considered the same problem from the standpoint of field ion microscopy. All four speakers had been charged by the organizers with emphasizing methods of distinguishing between ledges and dislocations. One of the most prominent (and colorful) of this group of speakers, Dr. M. Stobbs of Cambridge, made clear the theoretical as well as the experimental problems involved in making this distinction by referring to certain linear defects displayed in his slides as "thingies"! This issue has greatly worried us in our recent AFOSR-sponsored research, and it was somewhat of a relief to find that this concern is shared by the best of the experts in the field. However, it is now clear that special efforts must be expended upon making this very important distinction--particularly when the ledges are only a few atomic layers high.

Dr. U. Dahmen (Berkeley) and Prof. J. H. van der Merwe (Pretoria Univ., South Africa) spoke in detail about the role of structural ledges in compensating misfit. These ledges, originally reported by Hall, Aaronson and Kinsman in 1972, do not contribute (arguments of others to the contrary!) to growth. Since an effort has been recently made by J. W. Christian (Oxford) to deny their significance, it was encouraging to learn that in-depth theoretical interest in them is finally developing. (Recently, Dr. T. Furuhara observed structural ledges only two atom layers high with atomic resolution TEM during work in a Ti-Cr alloy sponsored by our AFOSR grant.)

A significant controversy has developed during the last decade between R. Trivedi (Iowa State) and C. Atkinson (Imperial College) concerning mathematical analyses of ledgewise growth whose implications are particularly important for growth taking place with diffusional interaction between adjacent ledges. Dr. M. Enomoto (National Research Inst. for Metals, Tokyo) has made empirical progress toward settling the argument by conducting computerized finite element analyses of ledgewise growth kinetics. His results agree only with those of Atkinson. They appeared to be accepted by all of the theoreticians in the audience, who comprise most of those now active in this research area. Mullins (Carnegie Mellon Univ.) has developed a macroscopic analogy to microscopic analytical treatments of ledgewise growth, and achieved good agreement with both the analytical treatment of Atkinson and computer modeling work of Enomoto. To this participant-observer, however, it is becoming apparent that the complex diffusion currents which develop during ledgewise growth in the presence of a composition change do an excellent job of concealing the "physics" of the problem, namely, the events taking place at the advancing risers of the growth ledges. It is beginning to appear that really fundamental studies of ledgewise growth, at least in solid → solid phase transformations, ought to be transferred to a massive transformation whose growth kinetics are not uncontrollably rapid, where long-range transport of solute and solvent is unnecessary. Further illustrating this point, Atkinson showed initial results from an analysis of the growth kinetics of kinks on the risers of ledges. Kinks have long been believed, particularly from studies on vapor → crystal and liquid → crystal growth, to be the regions on the risers of ledges at which growth actually takes place. The riser growth kinetics problem is even more complicated than the ledge growth one, again pointing toward "salvation" from computer modeling rather than analytical treatments.

Trivedi (Iowa State) showed convincing motion pictures of ledgewise growth during the solidification of transparent organic compounds. Abbaschian (Univ. of Florida) used indirect methods (because of the opacity of metals) to study solidification kinetics of pure metals. He also endorsed a ledge mechanism of growth, but a controversy arose about his interpretations which will not easily be settled because the method he used to make his observations was necessarily deductive. Aziz (Harvard) provided a fine theoretical analysis of solute trapping during solidification of silicon; he is one of the bright young theoretical and experimental stars of solidification in particular and of growth theory in general. Smith (IBM-Yorktown Heights) and Howe (Carnegie Mellon Univ.) both reported on the structure of solid:liquid interfaces observed by rapid quenching of the liquid to an amorphous solid. Controversy arose as to the relationship between a glass and a liquid, and thus as to the value of the results reported in the modeling context. However, Howe's results on ledge structures at one type of interface and an essentially smooth interface at another were quite convincing.

Keller (Inst. for Solid State Physics & Electron Microscopy, DDR) and then Mundschau (Berlin) reported on ledge structures during vapor/solid phase transformations. Both were excellent. However, the work of Mundschau (who has since returned to the U.S.), using a newly developed low-energy reflection electron microscopy technique, was especially important in demonstrating the ability of this approach to examine structural details on the surface of bulk specimens at very high resolutions without the use of replicas. This technique ought to find widespread application in many different fields, e.g., plastic deformation, corrosion, oxidation, etc. as well as in phase transformations.

A number of papers were presented on the role of ledges in specific types of phase transformation. Prominent among these was the demonstration by Shiflet (Univ. of Virginia) that the Hackney-Shiflet shared growth ledge mechanism for the edgewise growth of pearlite is also applicable in Ti-Fe and in an Fe-C-V alloy. If this mechanism does prove general for the pearlite reaction, it will surely be ranked as the most important experimental discovery relative to the pearlite reaction since the original observations on this microstructure by H. C. Sorby more than a century ago. Plichta (Michigan Tech) provided strong evidence for the ledgewise coarsening of $AlAg_2$ precipitates in an Al-Ag alloy and for the inapplicability of the now almost universally employed LSW analysis of coarsening, wherein uniform atomic attachment is assumed in both the presence and the absence of barriers to growth.

During the Panel Discussions which followed the presentation of individual papers, the lack of communication between workers in the different areas of phase transformations became apparent, particularly in respect of knowledge of the key experimental evidence in each area. The superiority of computer modeling over analytical studies for modeling ledgewise growth of precipitates was again quite well recognized. Problems of TEM studies and of nomenclature to be applied to linear defects at interfaces were bruited but no consensus was reached. The perennial argument of shear vs. diffusional growth flared again when Olson (Northwestern) made a particularly "daring" proposal through which structural ledges could participate in growth by shear; this was indignantly refuted by Aaronson--followed, of course, by a counter-refutation by Olson!

Perhaps the most disappointing aspect of this symposium to both of its organizers, Howe and Aaronson, was the lack of progress evident in identifying, characterizing and analyzing the origins of ledges and in studying the atomic mechanics of their lateral growth. We had both hoped that this symposium would reveal much new material in these areas, but except for Howe's pioneering studies on kinks at the risers of ledges this was not forthcoming. We continue to feel that these are the two main areas which should now be emphasized in order to spur most efficiently research on the growth aspect of all three types of phase transformation considered.

We express our gratitude for the AFOSR support received for the travel expenses of four of our overseas participants. All of the funds received from this grant were expended for this purpose.